

Lawrence Berkeley National Laboratory

LBL Publications

Title

Coupled Thermo-Hydro-Mechanical Processes in Fractured Rocks: Some Past Scientific Highlights and Future Research Directions

Permalink

<https://escholarship.org/uc/item/98h5q4c6>

Author

Tsang, Chin-Fu

Publication Date

2024-02-08

DOI

10.1007/s00603-023-03676-7

Copyright Information

This work is made available under the terms of a Creative Commons Attribution License, available at <https://creativecommons.org/licenses/by/4.0/>

Peer reviewed



Coupled Thermo-Hydro-Mechanical Processes in Fractured Rocks: Some Past Scientific Highlights and Future Research Directions

Chin-Fu Tsang^{1,2}

Received: 6 November 2023 / Accepted: 12 November 2023
© The Author(s) 2024

Abstract

Coupled thermo-hydro-mechanical (THM) processes in fractured rocks have been a topic of intense scientific research for more than 30 years. The present paper takes a look into the past and highlights some scientific advances which are of an unusual “out-of-the-box” nature, and then looks forward and discusses possible directions of future research in this interesting field of study. Concerning future research directions, we see a trend from a focus on coupled THM processes in single fractures or a few interacting fractures, to the study of coupled THM behavior in complex fracture network systems where the fractures act collectively giving rise to local stress concentration points and points of large pressure gradients. Three examples of future research directions are presented. First is an effort towards identifying characterizing parameters of a fracture network that play a direct controlling role in major coupled THM phenomena (such as induced seismicity and flow channeling), rather than parameters of stochastic distributions of fractures in the network. The second example of research direction is accounting for the heterogeneity and hierarchy of fractures in a fault or fracture zone which has been associated with major THM events in a number of geo-energy projects. The third example is at the opposite end of the first; here it is recognized that in some cases, the coupled THM processes in fractured rocks may be controlled dominantly by only a few key bridges. Identification, characterization, and evaluation of these key bridges should be one of the important research directions in the coming days.

Highlights

- The research into coupled thermo-hydro-mechanical processes in fractured rock over the last thirty years is reviewed.
- Three past scientific advances of an “out-of-the-box” nature are highlighted.
- Future research directions are discussed with three examples of potentially fruitful research directions.

Keywords Coupled processes · Hydromechanical processes · Thermomechanical processes · Fractured rocks · Fracture networks

1 Introduction

Coupled thermo-hydro-mechanical (THM) processes in fractured rocks are a topic of intense scientific research for more than thirty years, motivated initially by the need for performance assessment of nuclear waste repositories in

many countries and later by the interest in their role in scientific issues related to other geo-energy-related fields (Tsang 1987; Tsang et al. 2015; Figueiredo et al. 2020; Lei et al. 2017a, 2021; Lei and Tsang 2022; Sun et al. 2021; Jiang et al. 2022). These coupled THM processes arise because fluid flow and pressure (H) depend on fracture apertures which are dependent on local mechanical stress field (M) and on fluid pressure in iteration, and further the nuclear waste in the repository releases heat over thousands of years and this heat (T) could drive fluid flow through convection and induce thermal stresses in the system (Tsang 1987, 1991). The fractured rocks here refer not only to crystalline rocks and limestones where fracture occurrence is well known but also to early conditions near underground excavations in

✉ Chin-Fu Tsang
chin-fu.tsang@geo.uu.se

¹ Energy Geosciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA, USA

² Department of Earth Sciences, Uppsala University, Uppsala, Sweden

argillaceous and clay rock and even in salt formation under certain unsaturated and humidity situations. A comparative review of coupled THM processes in these different rock types in the excavation damaged zone around underground openings is given in Tsang et al. (2005).

Studying and modeling coupled THM processes in fractured rocks to meet the need of waste repository performance assessment present particular challenges far beyond conventional engineering projects. First, such performance analysis requires predicting into hundreds of thousands of years, which means that the underlying science in the various aspects of modeling of these processes over a time frame far into the future must be correct. Secondly, the current approach to nuclear waste disposal assumes that there will be no long-term monitoring and remediation planned, which means that we need a much more careful procedure in uncertainty assessment and confidence building.

The present paper takes a look into the past and highlights some scientific advances which are of an unusual nature, and then looks forward and discusses possible directions of future research in this interesting field of study.

2 Some Past Scientific Highlights

In this section, instead of presenting advances in scientific understanding and modeling techniques over the past years associated with particular coupled THM processes, which are well reviewed in the literature (Birkholzer and Bond 2022; Birkholzer et al. 2019; Hudson et al. 2017; Tsang et al. 2009; Stephansson et al. 1996), we shall highlight three major scientific advances which are of a special “out-of-the-box” character. They are firstly the need and importance of employing multiple alternative conceptual models in the study of coupled processes, and secondly the recognition of the iterative interplay between modeling objectives, site characterization plans, and predictions with uncertainty assessment. Thirdly, a comprehensive understanding has been obtained through a comparative study of coupled processes and their characteristics in excavation damage zones across four different rock media: crystalline rocks, argillaceous rock, plastic clays, and salt. Although these rock types are very different, commonalities in coupled processes have been identified and compared, and deeper insights developed.

2.1 Multiple Conceptual Model Analysis

The application of numerical models to study, for example, fluid flow and mechanical deformation in a rock mass under changes in pressure and stress at its boundaries usually involves the selection of a conceptual model for the rock mass, determination of model parameters through analysis of

available field data, validation of the model behavior against some field or laboratory experiments with possibly parameter calibration, and then performing predictive modeling studies of flow and rock deformation over the life time of interest. Very seldom in a practical project are more than one conceptual model of the rock mass used for such work. A major advance is the recognition of the usefulness and even the importance of using multiple conceptual models to address the problem. The basic reason behind this is that the rock mass is heterogeneous, anisotropic, and generally complex, and a conceptual model is necessarily a simplified representation to make it computationally feasible to perform various analyses of its behavior under coupled processes. However, no simplified model can claim to be uniquely able to represent the real system in a full way. Furthermore, different mathematical solution schemes and mesh designs have been developed to calculate the flow and deformation on the different conceptual models. It has been found that simultaneous use of several alternative conceptual models and solution schemes to address the same problem with a joint analysis of the results from these alternatives yields important new information on prediction uncertainty and points to desired new field data that may reduce these uncertainties.

An example of this multi-conceptual model study is provided by Wilcock (1996) for the investigation of flow into a tunnel excavated in a 2D fracture rock domain and the associated rock deformation, with a heat source under the tunnel representing a nuclear waste deposition borehole. Figure 1 shows the problem definition. The left side of the figure shows a representation of the rock domain with the position of the tunnel and heat source, and also the specified boundary hydraulic and stress conditions. The heat source will start at time t^* and its thermal flux F_t follows a prescribed exponential decreasing trend β with time t from an initial value Q_0 corresponding to that from radioactive decay of the waste:

$$F_t = Q_0 e^{-\beta t} \quad (1)$$

Calculations were to be conducted (Fig. 1, right side) in three steps: initialization of the hydromechanical equilibrium before tunnel excavation, excavation at $t=0$, and start of heating at time $t=t^*$ for 100 years. The domain has 6580 fractures (Fig. 2) with density, length, and orientation distributions similar to those found at the Sellafield site in UK.

The problem was one of the tasks of the international collaborative research project DECOVALEX (Stephansson et al. 1996), and it was studied by eight research teams, who tried to represent the domain with their best effort, using different conceptual models ranging from discrete fracture network with all the fractures, or a reduced network with only the relatively large fractures, to equivalent porous

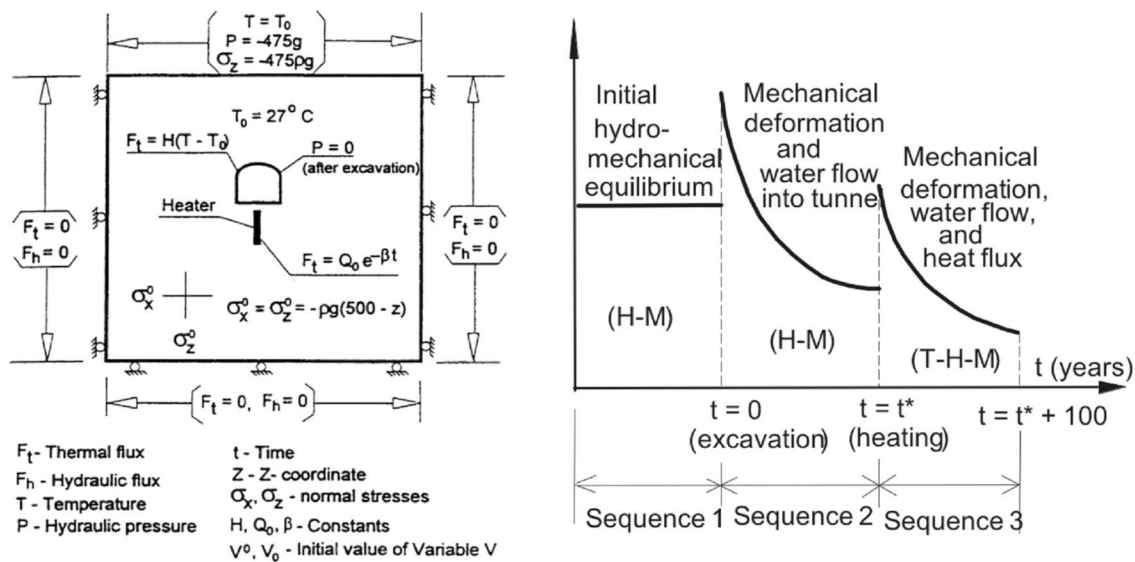


Fig. 1 Problem definition for a generic study of coupled THM processes in the near field of a nuclear waste repository tunnel. From Wilcock (1996)

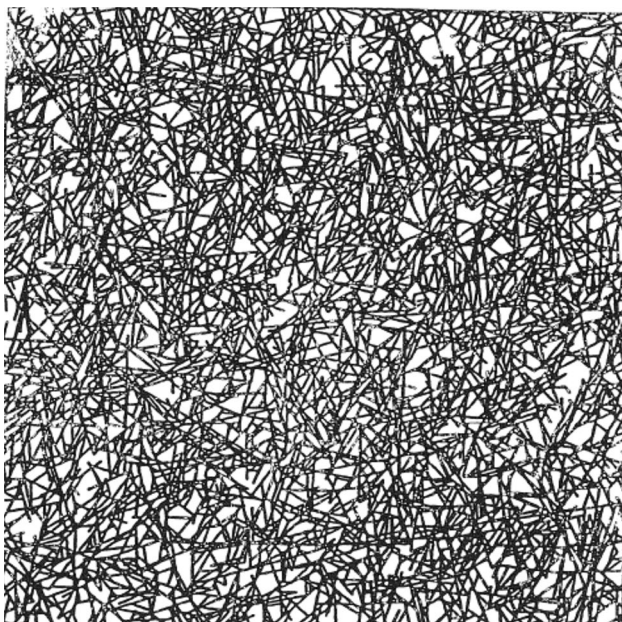


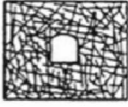

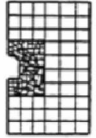

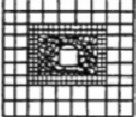

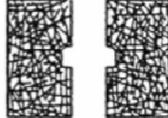

Fig. 2 A network of 6580 fractures used in a generic study of coupled THM processes in the near field of a nuclear waste repository tunnel. From Wilcock (1996)

medium representations, and using different numerical methods such as finite difference method, finite element, and discrete element methods. Details of these alternatives are summarized in Fig. 3, and more descriptions may be found in Wilcox (1996). There was no a priori reason to decide which conceptual model and which numerical method are better than all the others, and the results are compared and

studied together, to obtain insight not only on the coupled THM effects in such a problem but also on the uncertainty and confidence levels in the prediction of system behavior. For example, it was shown (Wilcox 1996) that predictions on temperature distribution into the next 100 years and more are very good, independent of the conceptual model and numerical methods used by the different teams, and predictions on stresses are fairly good, but there were great discrepancies among the results from the different teams on water flux into the tunnel, pointing out the importance of fracture connectivity to the tunnel, which was represented in different ways in these conceptual models. Thus, fracture connectivity in the vicinity of the tunnel was identified to be a key element for follow-up field studies and model evaluation if water flux into tunnels is an issue for the long-term performance of a waste repository.

As can be seen in the above example, important insights are obtained by multiple conceptual model analysis, which cannot be gained through the study using only one conceptual model (even with some calibration exercises), as has been generally practiced. This approach has been applied in the study of a number of other tasks in the later phases of the DECOVALEX project (Birkholzer and Bond 2022; Birkholzer et al. 2019). As an additional example, Sawada et al. (2005) conducted a study of groundwater flow in Mizunami Underground Research Laboratory in Japan, where the authors provided five modeling groups with site characterization data from a surface investigation stage at and around the underground laboratory site to develop their own conceptual models of flow and transport in the subsurface. Comparisons of the results from these five alternatives were used

Fig. 3 Eight different research teams and a variety of different conceptual models and numerical methods used to study the coupled THM processes in the near field of a nuclear waste repository tunnel. For details, please see Wilcock (1996)

| | |
|---|---|
| <p>AEA (NAPSAC code, DFN model)</p> <p>Complete and explicit representation of 6580 fractures by DFN method, without heat and rock deformation, but with analytical model for stress approximation.</p> |  |
| <p>CEA/DMT (CASTEM 2000 code, FEM model)</p> <p>Equivalent continuum approach with FEM method (1344 elements, 4216 nodes), homogenization (scale 25 x 25 meters) by Crack Tensor theory [24].</p> |  |
| <p>CNWRA (UDEC code, DEM model)</p> <p>Vertical symmetry and simplified fracture network with 295 fractures, 337 blocks, 1540 finite difference elements, and 10853 nodes. A small inner region with random fractures and larger outer region with regular artificial fractures.</p> |  |
| <p>ITASCA (FLAC code, FDM model)</p> <p>Equivalent continuum approach with FDM (735 finite difference elements and 792 nodes) without formal homogenization. Vertical symmetry and inhomogeneous permeability.</p> |  |
| <p>INERIS (UDEC code, DEM model)</p> <p>Simplified fracture network with inner region of random fractures and outer regions of regular artificial fractures (564 fractures, 677 blocks, 24391 finite difference elements, and 16791 nodes).</p> |  |
| <p>KPH (THAMES code, FEM model)</p> <p>Equivalent continuum approach with FEM method (674 elements, 2127 nodes). Homogenization (scale 10 X 10 meters) by Crack Tensor theory [24]. Heat convection considered.</p> |  |
| <p>NGI (UDEC code, DEM model)</p> <p>Two model of vertical symmetry (one left half and one right half) with simplified fracture network without heating, about 512 fractures, 510 blocks, and 1580 finite difference elements.</p> |  |
| <p>VTT (UDEC code, DEM model)</p> <p>Vertical symmetry (left half) with simplified fracture network, 814 fractures, 496 blocks, 1308 finite difference elements, and 2222 nodes.</p> |  |

to identify those aspects of the hydrogeological parameters or system characteristics that were well characterized by surface data and other aspects with large uncertainties that would require further surface or subsurface investigations.

2.2 Iterative Interplay Between Modeling Objectives, Site Characterization Plans, and Prediction Modeling with Uncertainty Assessment

The second “out-of-the box” past accomplishment to be highlighted concerns a recognition of the iterative interplay between model objectives, site characterization design, and model predictions. In conventional work, the model objectives are often defined by the needs of a geotechnical project, then a plan for field surveys and testing programs is designed and executed, and finally model calculations are conducted

with predictions made, all in a one-way fashion. However, this practice does not work for projects with the need for predictions of system behavior many years into the future, even hundreds of thousands of years in the case of performance assessment of nuclear waste geologic repositories.

Let us consider the three elements of such a project by commenting first on the site characterization design, then on model predictions and finally on model objectives. A site needs to be characterized by geological surface and sub-surface surveys to detect features such as fault zones and density of fractures with estimates of their sizes and orientations, and then by borehole measurements to evaluate certain characteristics, such as rock permeability for fluid flow and the in situ stress field. These are needed as input to model calculations that provide predictions of interest to the project. It can be quickly realized that it is impossible to

fully characterize a geologic system because of its intrinsic heterogeneity at multiple scales.

Model predictions based on models with incomplete data will obviously contain certain degree of uncertainty. An assessment of uncertainty may suggest additional site data needs, thus providing a feedback to the need for additional site characterization activities. However, even in the case where the site is characterized to good details, the numerical model used often cannot handle such details because of computational time and accuracy limitations, and some simplifications have to be made when developing conceptual models, such as network models, stochastic models, or equivalent porous medium models, to represent the system for model calculations. This is in addition to possible errors due to finite mesh designs often used in various numerical methods. Therefore, model predictions need to be accompanied by a careful evaluation of uncertainty ranges. Predictions without estimates of associated uncertainty ranges are not so meaningful.

This leads to the issue of defining model objectives. Predictions of certain quantities very long term into the future are often associated with very large uncertainties, even orders of magnitude. For example, if one is required to predict tracer arrival time at a spatial point after several thousands of years, the uncertainty range could be several orders of magnitude, because of the lack of knowledge in the geologic structure at fine local scale around the observation point and in how the site structure will change over the next thousands of years because of coupled THM and chemical effects. However, if one is to predict the averaged tracer arrival time over a large region around that point, the prediction will have a much reduced uncertainty. Thus, we need to modify the ambition in the model objectives, and many times a limited ambition may still satisfy the overall project objectives. A modified objective would also suggest an adjusted optimal site characterization design at a more reasonable cost.

Thus, we see that the three elements of model objectives, site data, and prediction need to be considered jointly and iteratively. This is discussed in more detail in Tsang et al. (1994), Tsang (2005), and Tsang and Niemi (2013).

2.3 Coupled Processes and Characteristics in Excavation Damaged Zones Across Four Different Rock Types: Crystalline Rocks, Argillaceous Rock, Plastic Clays, and Salt

The third highlight of past accomplishments involves a comparative review of coupled THM processes and

characteristics in an excavation damaged zone (EDZ) across four different rock types, crystalline rocks, argillaceous rock, plastic clays, and salt (Tsang et al. 2005). EDZ is a zone around deep tunnels or underground openings which has undergone significant hydromechanical changes because of release of stresses at the walls of the opening. These changes include opening or closing of fractures and slip of preexisting fractures in the neighborhood of the tunnel (Lei et al. 2017b), with potentially orders of magnitude changes in flow permeability in the EDZ.

Tables were developed (Tsang et al. 2005) in the context of performance of nuclear waste geologic repository in the four types of rock formation to summarize (i) the key processes, (ii) geological parameters, and (iii) technical issues associated with EDZ in the four rock types side by side. These key processes and technical issues were discussed according to stages of repository development: (a) the excavation stage, (b) the open tunnel stage, (c) the early closure stage which includes water resaturation of the tunnel region and heating from deposited radioactive waste, and (d) the late closure stage which include cooling and rock self-sealing process.

A synthesis of the current state of knowledge of EDZ for the four rock types was then made to identify the many similarities as well as differences among them in the EDZ evolution (Tsang et al. 2005). For some processes, the behavior of one rock type represents the extreme-parameter case of another. Furthermore, knowledge of one rock type may find a correspondence in another rock type and thus alert a researcher to seek similar characteristic in another. For example, the highest permeability in EDZ in argillaceous clay rock is not found at the tunnel wall, but at about 0.6 m into the rock. This observation may encourage research to find similar behavior in other rock types. Another example is a realization from this comparative study that, in general, EDZ behavior is a dynamic problem that depends on changing conditions, such as moisture in the tunnel which varies from the open tunnel to the closed tunnel period with water resaturation and thermal input from the stored radioactive waste. All these changing conditions may affect rock strength and creeping properties in the different rock types. The multiple rock-type considerations help remind us not to neglect slow processes, related to not only rock property changes but also processes such as the self-sealing phenomenon due to long-term hydrochemical processes, especially when we consider predictions into many thousands of years.

Furthermore, observations, concepts, testing methodologies, and numerical models are, in a number of cases, transferrable among studies of the four rock types. The

Fig. 4 Mesh design for a 1000 m × 1000 m 2D rock domain and the fracture network in its 100 m × 100 m center region used for studying fluid injection-induced microseismicity (from Jia et al. 2022b)

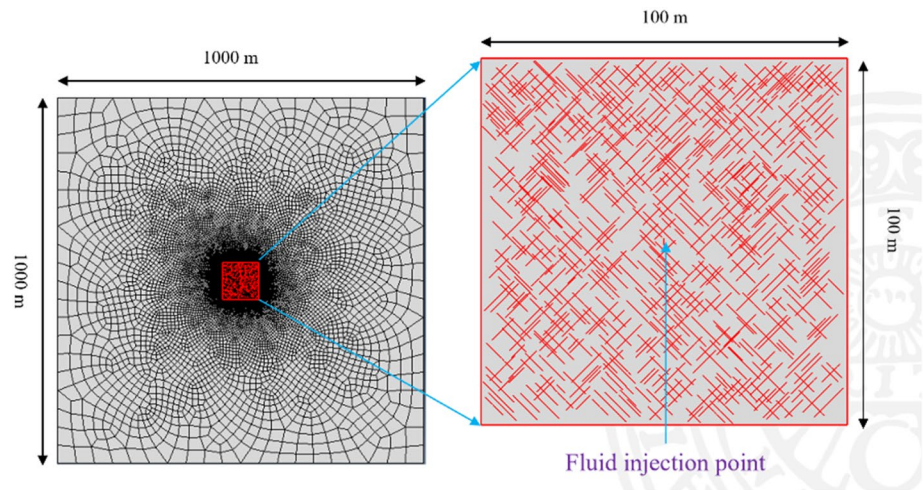
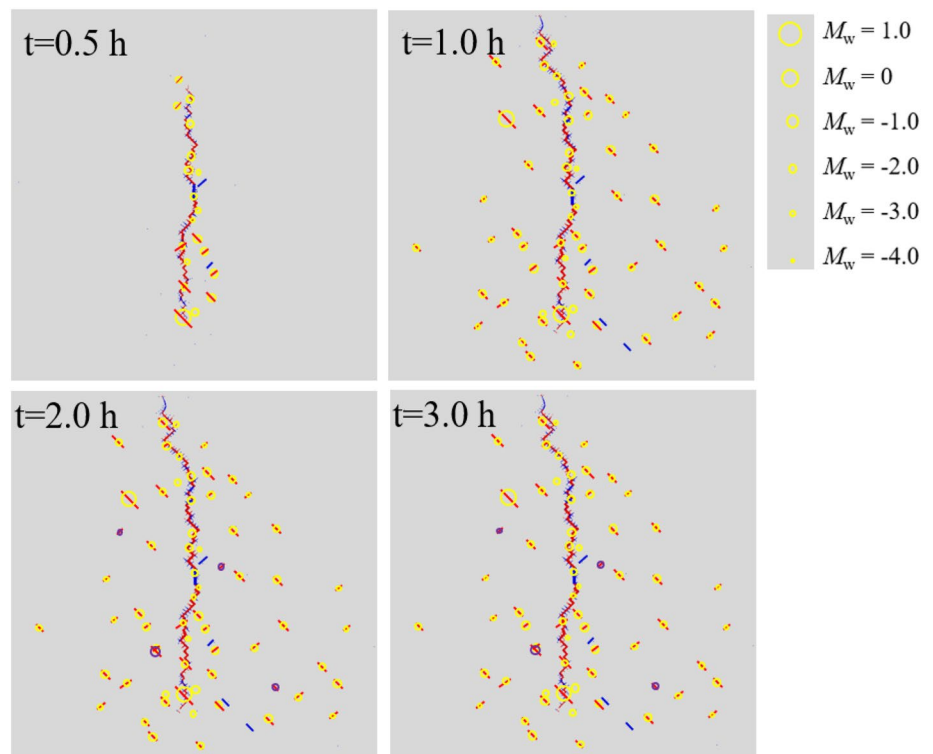


Fig. 5 Cumulative microseismic events (yellow dots) with time and their magnitudes M_w , with fluid injection of one hour and then monitored for another two hours. The red lines indicate fractures with shear displacement and the blue lines fractures with tensile failure. There are 58 events during injection and 4 events after injection is terminated. From Jia et al. (2022b)



consideration of coupled THM processes in EDZ and its evolution simultaneously in the four very different rock types has provided us with deeper insight and enhanced confidence in our understanding of EDZ in any one particular rock type of interest.

As an extension of the realization that cross fertilization and new insights can be obtained by comparative study of coupled THM processes in different rock types, scientific advances can also be gained in a similar way through the parallel coupled processes studies for different geo-energy applications, such as nuclear waste repository performance

assessment, optimization of enhanced geothermal systems, stability of underground openings, and CO₂ geosequestration. In particular, the issues and concepts discussed in this paper may be found useful in research for all these different practical applications.

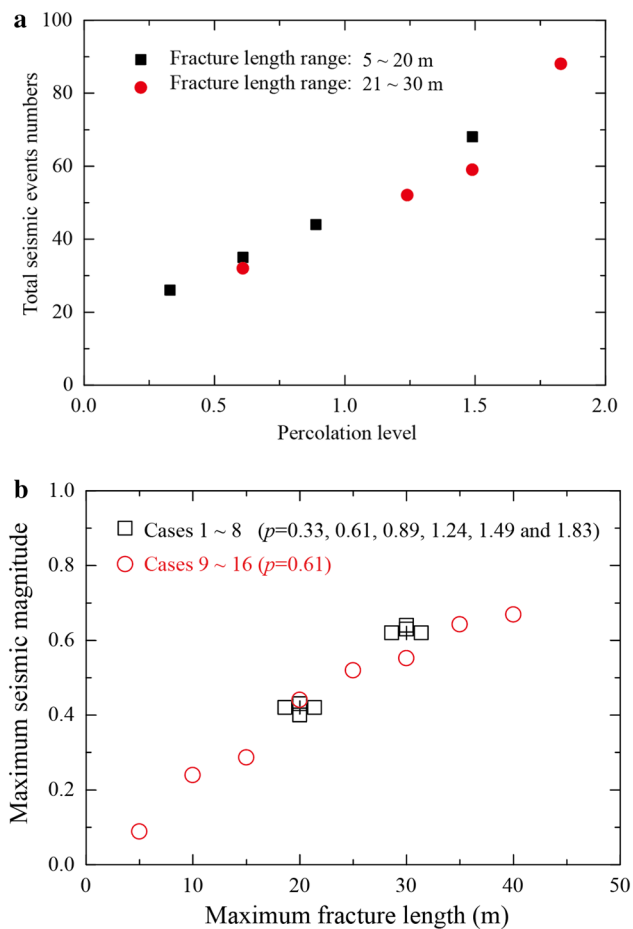


Fig. 6 a. The number of microseismic events as a function of percolation level p defined by Eq. (2). From Jia et al. (2022b). b The maximum magnitude M_w of microseismic events as a function of maximum fracture length in the fracture network for different values of percolation level p , including those both below and above the p_c value. From Jia et al. (2022b)

3 Some Current and Future Directions of Research in Coupled THM Processes

As mentioned earlier, many significant results from coupled THM processes research over the past few decades have been well summarized and reviewed by Birkholzer and Bond (2022); Birkholzer et al. (2019); Hudson et al. (2017); Tsang et al. (2009), and Stephansson et al. (1996). These publications also give references on specific topics in this field. Looking into the future, we see a trend from a focus on coupled THM processes in single fractures or a few interacting fractures, to the study of coupled THM behavior in complex fracture network systems. The former includes tensile and shear deformations on a fracture as well as fracture propagation under changing boundary stress conditions or

under fluid injection. Fluid injection includes the case of cold-water injection into subsurface hot rock in enhanced geothermal systems (EGS) where the temperature difference introduces thermal-induced stress changes as well as thermal convective flow (Jia et al. 2022a; Figueiredo et al. 2020). In addition, interference in THM behavior among a few fractures has also been studied, including the so-called stress shadow effect and influence of nearby fractures or bedding planes on a fracture involved in high pressure injection (see, e.g., Figueiredo et al. 2017).

Current and future coupled THM research are trending toward study of complex fracture networks with many intersecting fractures in a 3D rock domain with THM behavior depending on simultaneous effects of all the fractures present in the network. These networks may include curved fractures, fractures with dead ends, and isolated fractures or isolated fracture clusters (Latham et al. 2013; Lei et al. 2014, 2015, 2016), which are often ignored in studies of fluid flow, but may play a significant role in coupled HM behavior of the network, especially in 3D (Lei et al. 2017c). Furthermore, fractures in the network are often non-isotropic and also may be denser in some regions than others (Lei and Wang 2016), with strong variations in the neighborhood of a fault or fracture zone. Such a fracture network subjected to stress changes and pressure gradients presents a complex picture of stress and pressure distributions (e.g., Figueiredo et al. 2015; Lei et al. 2020). Thus, local values of stress magnitudes, orientations, and ratios may well be very different from boundary stresses (Gao et al. 2019), and high stress concentration points and high hydraulic gradients may be found in different points of the network (Lei and Gao 2018, 2019), which can play a major role in flow channeling (Tsang and Neretnieks 1998; Min et al. 2004) and in potential microseismic events (Lei and Tsang 2022; Jia et al. 2022b). All these have to be understood and further methods need to be developed for their evaluation as to their coupled THM behavior. Below we shall present three examples to illustrate the above discussion. While these examples have a focus on HM processes, the concepts are general and are an important component in THM behavior of fractured rocks. The thermal component can be straightforwardly included through the addition of thermal stress and convection effects.

3.1 A Study of Fluid Injection-Induced Microseismic Events as a Function of Key Parameters Characterizing a Fracture Network

The first example is a suggestion of two characterizing parameters of a fracture network system that can serve as controls to fluid injection-induced microseismic events by Jia et al. (2022b). In this work, a 2D fracture network is considered with two orthogonal sets of fractures with a

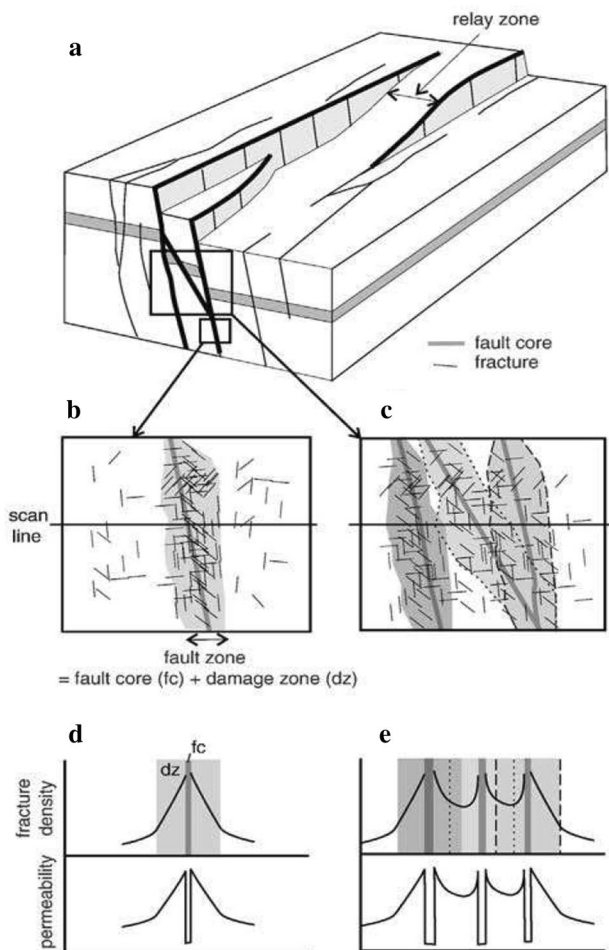


Fig. 7 Schematic diagram of a normal fault zone (a), where the width of fault zone may be defined to include the fault core and surrounding damage zone (with high fracture density) in the case of a single core (b), and in the case of multiple cores (c). The fracture density and permeability as a function of distance from the core(s) for the two cases are shown in (d) and (e), respectively. From Bense et al. (2013)

length distribution over a limited range of values, as shown in Fig. 4. The maximum stress is applied vertically between the top and bottom boundaries. Then fluid is injected into the middle of the fracture network (see Fig. 4) for a time period of one hour with the coupled HM modeling continued for another two hours. The induced tensile and shear fracture movements are calculated and induced seismic events at various points in the network are identified and their magnitudes calculated. The results are presented in Fig. 5, where a dominant injection-induced fracturing is seen in the direction of maximum stress, as expected. For this particular case, 58 events occur during the injection period, along with 4 events occurring after injection is terminated.

Jia et al. (2022b) proposed two parameters to characterize the network that may act as controls on the microseismic

events. First is a percolation parameter p which is found to correlate with the number of events and the second the maximum fracture length in the network which is found to correlate with the maximum seismic magnitude. Here the percolation parameter for a 2D domain is defined (Robinson 1983) as

$$p = \sum (\ell/2)^2 / L^2 \quad (2)$$

where ℓ is the fracture length, the summation is over all fractures in the network, and L is the domain size. According to Robinson (1983), there is a one-to-one relationship between p and the average number of intersections that a fracture in the network is intercepted by other fractures in the network. A critical percolation level p_c is the value below which flow cannot flow across the domain of size L when a pressure step is imposed across it, because the network of fractures is not connected from the high to the low pressure side. The p_c value is a function of the angle between the two sets of fractures in the 2D domain. Through a numerical study Robinson (1983) found that p_c has a value of 1.45 to 2 corresponding to an angle between the two fracture sets being 90° to 45° , respectively.

Jia et al. (2022b) conducted a series of numerical experiments with two orthogonal fracture sets with different ranges of fracture lengths. Their results are summarized in Fig. 6a and b, which clearly shows an almost linear relationship between the number of calculated microseismic events with the percolation parameter p independent of fracture length (Fig. 6a), and also an almost linear relationship between the maximum magnitude of the microseismic events, and the maximum length of the fractures in the network independent of the percolation level p , from below to above its critical percolation p_c value of 1.45 (Fig. 6b).

The study can be extended to 3D fracture network of volume V , in which case the percolation parameter (Maillot et al. 2016; deDreuzy et al. 2000) can be rewritten as

$$p = \sum \pi^2 (\ell/2)^3 / V. \quad (3)$$

The above example demonstrates a potentially fruitful research direction, that of searching for and defining suitable characterization parameters of fracture networks that may be directly associated with observable results of coupled processes such as injection-induced seismicity. They may be directly measurable in a site investigation program and would thus be much more useful than specifying the underlying statistical distributions of fracture length, orientation, and aperture of the network with uncertainties over multiple realizations. In the example, the characterization parameters related to fluid injection-induced microseismicity are proposed to be the percolation parameter and the maximum fracture length. This suggestion needs

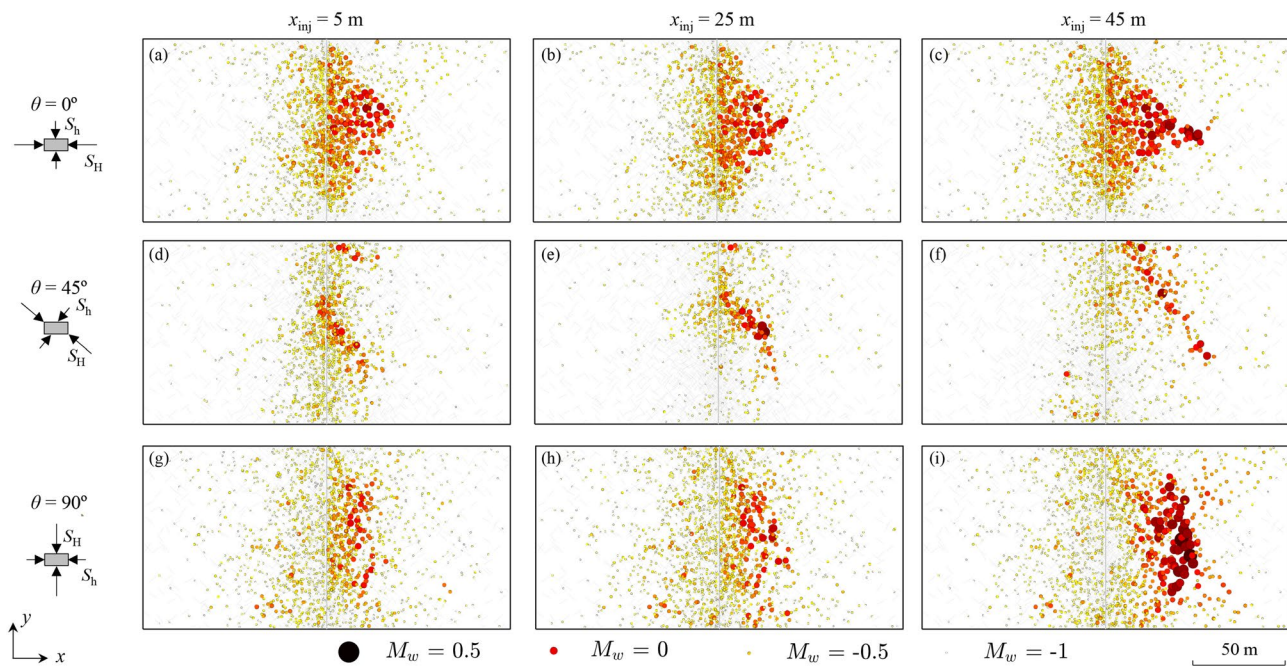


Fig. 8 Fluid injection-induced microseismicity in a fault zone with a fault core under different far-field stress orientations and with different injection distances from the core. From Lei and Tsang (2022)

to be confirmed through further studies, and perhaps other and better characterization parameters will be identified.

3.2 Coupled THM Processes in Complex Faults or Fracture Zones

Coupled THM processes are found to be strongly affected by the presence of faults or fracture zones. These geological features are often represented by very simple conceptual models such as parallel surfaces with equivalent porous medium between them which has some specified hydraulic and mechanical properties. This approach may be adequate if one considers only fluid flow or only mechanical deformation. For coupled THM processes which give rise to flow channeling and microseismicity, such a simple representation may not be adequate. It is important to re-examine coupled THM processes considering the details of the complex structure of the fracture zone. Figure 7 shows a possible schematic structure of a normal fault zone from Bense et al. (2013). It is shown that the fault may contain one or more strands of very low-permeability core with a damage zone around it, whose fracture density or permeability decreases as a function of distance from the core (Brixel et al. 2020a, b).

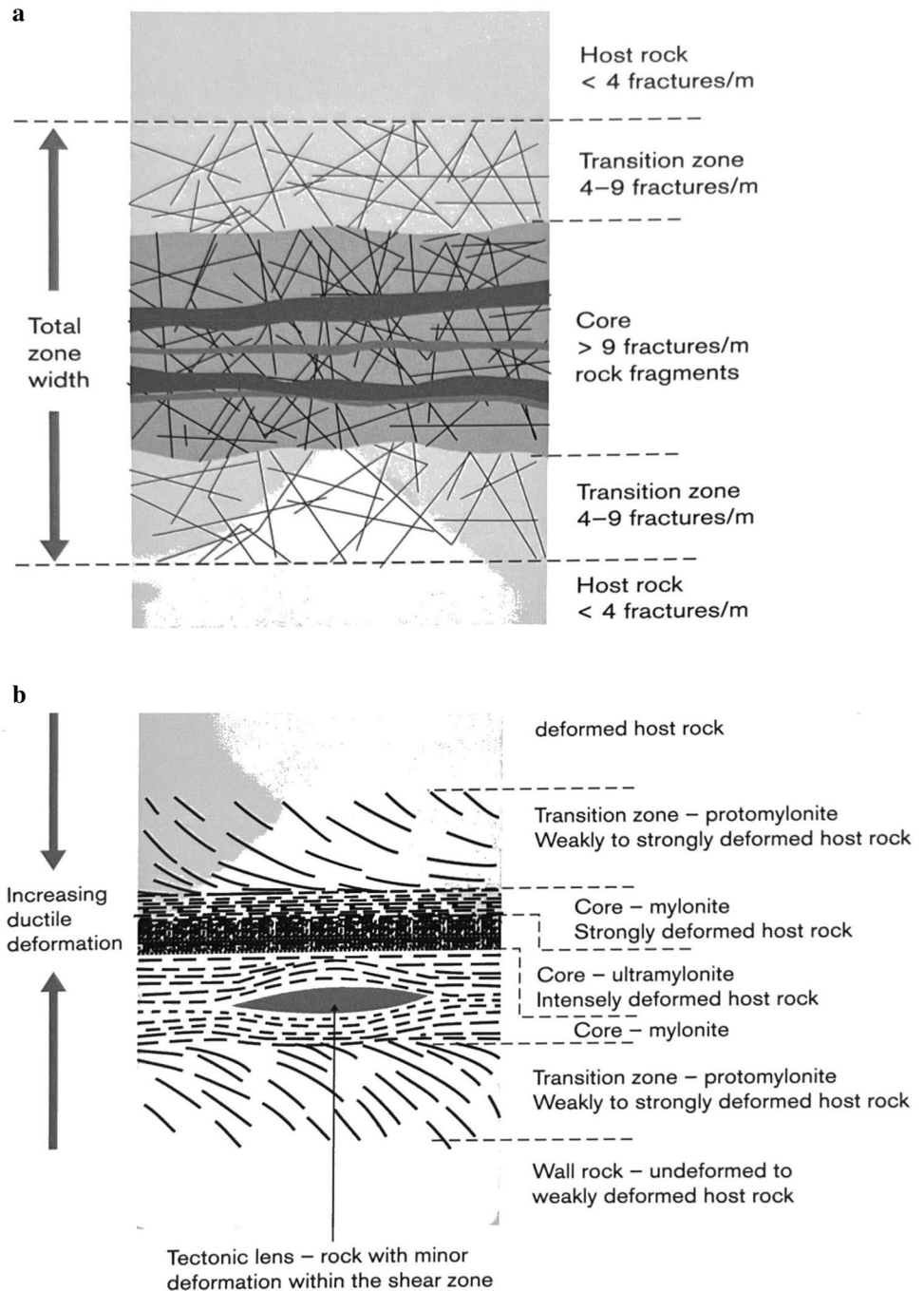
A fault structure like the one shown in Fig. 7d is used in the study of fluid injection-induced microseismicity by Lei and Tsang (2022). In this work, a 2D study area of 200 m by 200 m located at 3600 m depth is assumed, and a fault

located at the center of the domain has a 10-cm fault core bounded by a damaged zone characterized by a network of 5-m-long fractures. There are two fracture sets with mean orientations of 45° and 135° , respectively, related to the fault axis and a directional dispersion of $\pm 15^\circ$. The fracture intensity is highest at the core boundary at 0.5/m, which decays exponentially away from the core to a value of 0.1/m at about 35 m from the fault core.

Figure 8 shows some results on fluid injection-induced seismicity from the study as a function of the orientation of the stresses imposed on the domain boundaries and the distance of the injection point from the fault core. The resulting clouds of seismic events and their magnitudes clearly display the dependence on these parameters. It is interesting to note that, though the fault core has an almost zero permeability (10^{-20} m^2 , as compared with the individual fracture residual permeability of 10^{-11} m^2), some microseismic events are still found on the side of the core opposite to that of the injection point. A study of flow and tracer transport, without calculation of induced seismicity, was also performed by Tsang and Doughty (2003) for the case of a double-core fracture zone system.

The above is an example of study on a relatively simple fault core structure. Munier et al. (2003) reviewed the structure of faults in crystalline rocks and presented schematic examples of a brittle deformation fracture zone (Fig. 9a) and a ductile shear zone (Fig. 9b). Good reviews of internal structures of faults zones and their properties are also

Fig. 9 a. Schematic diagram of a brittle deformation zone. From Munier et al. (2003). b. Schematic diagram of a ductile shear zone. From Munier et al. (2003)



provided by Wibberley et al. (2008) and Faulkner et al. (2010). How these details in fault structures would affect coupled THM processes giving rise to microseismicity, flow channeling, and anisotropy is very much an open question.

3.3 Compartments and Key Bridges in Fracture Networks

Another interesting and potentially important future research direction is the occurrence of hydraulic compartmentation of

a fracture network domain, especially for low-permeability fractured rocks. Sawada et al. (2000) conducted a field investigation of fracture rock at the Kamaishi Mine in Northeast Japan and found from a measurement of pressure distribution over a region the presence of areas or compartments with similar pressures which differ from those of neighboring areas. These compartments were confirmed by dipole tracer tests. The occurrence of hydraulic compartments can be understood from the fact that fractures in a network have a

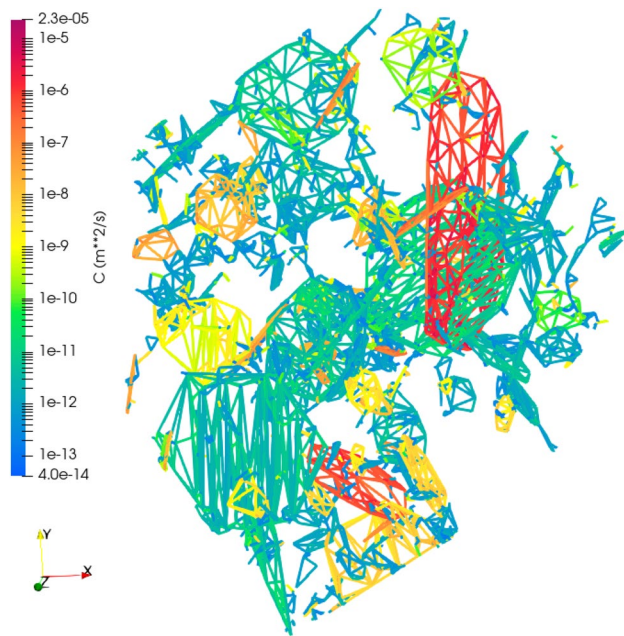


Fig. 10 A 3D network of 3200 fractures based on data from Forsmark, after removal of isolated fractures and fracture clusters, with their conductances. From Sharma et al. (2023)

wide range of permeability values and sizes and are spatially distributed with variable densities (clusters).

More recently, a numerical study was conducted by Sharma et al. (2023), who calculated flow and transport in a fracture network based on data from field measurements in low-permeability rock at the Forsmark site in Sweden. The Swedish nuclear waste management company SKB developed two discrete fracture networks (DFNs) for a region of this site (Fox et al. 2007; Follin 2008). One network is called GeoDFN which is based on mapping of fracture traces on outcrops and in boreholes, and the second, called HydroDFN based on downhole flow measurements. Thus, the HydroDFN can be considered as a subset of GeoDFN, which includes only those fractures with a hydraulic conductivity that is above the sensitivity limit of the downhole flow measurement. Sharma et al. (2023) constructed a fracture network from the HydroDFN and GeoDFN for a 3D domain $714 \text{ m} \times 714 \text{ m} \times 200 \text{ m}$, with about 9000 fractures. Calculation of the 3D percolation parameter using Eq. (3) yields a value of 4.8.

Sharma et al. (2023) then employed a simple technique to find and remove isolated fractures and fracture clusters and obtained a fracture network shown in Fig. 10 consisting of 3200 fractures. By applying a pressure step between the northwest and southeast boundaries, while keeping all other boundaries closed, pressures and flow rates in the channels

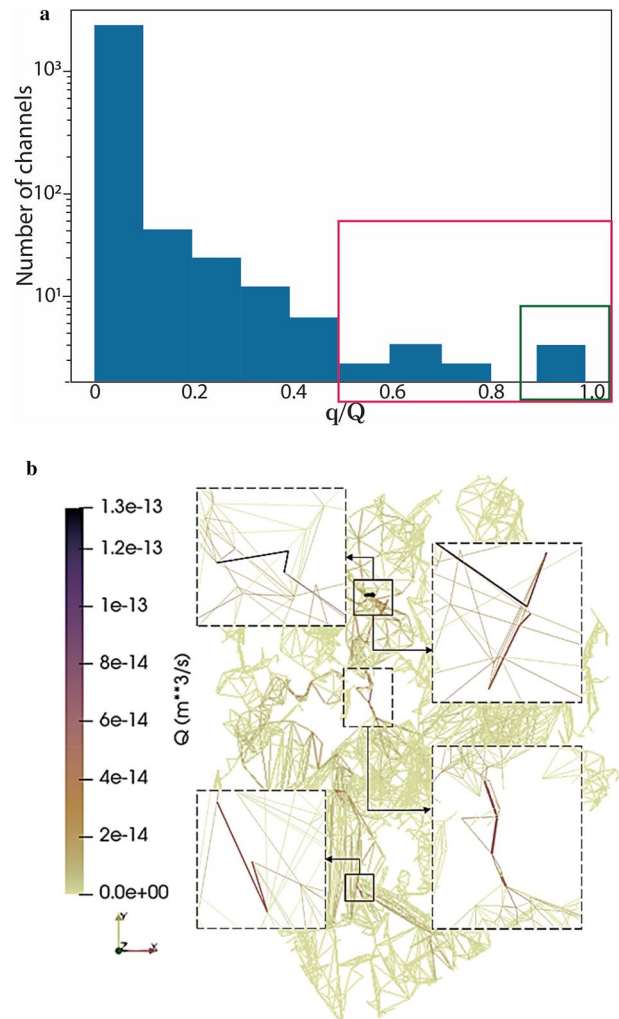


Fig. 11 a. Identification of key bridges for flow and transport in the 3D fracture network from histogram of flow rates in the channels connecting fractures. The high flow rate values indicate those channels forming a few key bridges. From Sharma et al. (2023). b. Locations of three key bridges for flow and transport in the 3D fracture network corresponding to those identified in Fig. 11a, indicated by the three small boxes in the center, with an amplified view in the four bigger boxes (the top small box is shown in two big boxes from two different view directions in 3D). From Sharma et al. (2023)

connecting the fractures were calculated. It is found that large pressure gradients occur in a few points in the network, which have large local flow rates as shown in Fig. 11. The picture that has emerged is a flow domain with a few flow compartments connected by a few key bridges or bottlenecks, confirming the observation of Sawada et al. (2000). These key bridges can be identified by their high flow rates (Fig. 11a), and they essentially control the flow and transport through the whole network. In this particular case, there are

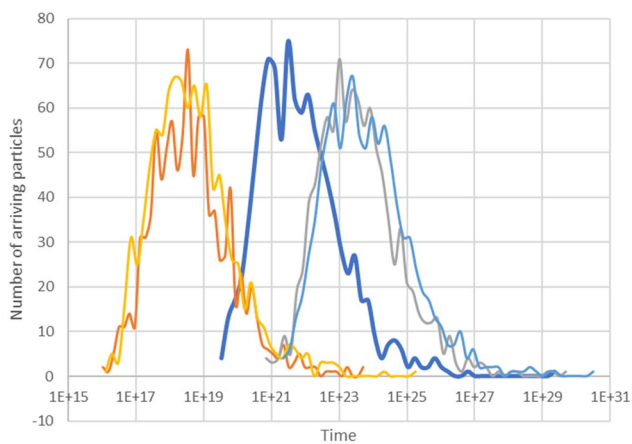


Fig. 12 The effects of changing the conductances of one or three key bridges by a factor of 0.01 or 100 (potentially due to coupled THM or long-term chemical effects) on the arrival of tracer particles at the SW boundary from particle injection at the NW boundary. The blue line is the original result; the orange and yellow lines are those from increasing the conductances of the center key bridge and all three key bridges, respectively; and the gray and light blue are those from decreasing the key bridge conductances. The horizontal axis is time in relative units. From Sharma et al. (2023)

three key bridges (Fig. 11b) formed by fractures from the GeoDFN.

It is interesting to note that these key bridges may be different from the so-called red link which is defined by Davy et al. (2006) as the fracture whose presence or absence results in the fracture network to be above or below the percolation threshold p_c . As pointed out above, the 3D fracture network studied by Sharma et al. (2023) has a percolation parameter value p of 4.8, well above the percolation threshold p_c , which, according to deDreuzy et al. (2000), is 2.55 or lower for a network of random fractures with a wide range of fracture eccentricities and fracture length power-law exponents. In other words, for a fracture network even above its percolation threshold, key bridges can be found which join different fracture clusters in the flow domain and which play a controlling role in flow and transport through the system.

Now if the permeability values of these key bridges change, for example, because of mechanical deformation in a coupled THM process or because of chemical changes such as pressure solution, the flow and transport will be strongly affected. This is demonstrated in Fig. 12, which shows that if the permeability of the three key bridges, or even just the middle one bridge in Fig. 11b, is adjusted up or down by a factor of 100, tracer breakthrough time from the northwest to southeast boundaries can be changed by two orders of magnitude.

This example points to an important direction of potential research into coupled THM processes in fracture rocks that, in addition to efforts toward upscaling and homogenized representation of fracture rocks to calculate their

equivalent permeabilities, etc., there is a need for research to go the opposite direction to identify key bridges in the fracture network, especially for the case of low-permeability rocks, which may control the coupled behavior of the whole system. These key bridges represent flow connections with high pressure gradient and areas with high stress concentrations. A study of the spatial distribution and the physical and chemical characteristics of these key bridges, and what will happen with time due to coupled processes at these points will be of great importance for flow and transport predictions.

4 Summary and Remarks

Much progress has been made over the past decades on research of coupled THM processes in fracture rocks, particularly through the international cooperative project DECOVALEX. Advances in many aspects of the work have been summarized in a number of major publications (see, e.g., Birkholzer and Bond 2022; Birkholzer et al. 2019). The present paper highlights three “out-of-the-box” insights obtained from these efforts, namely, the importance of simultaneously studying coupled processes using multiple conceptual models and numerical techniques; the iterative interplay between model objectives, site characterization plans, and predictions with uncertainty assessment; and the usefulness of parallel comparative study of the processes in different rock types and even in different geo-energy projects.

A consideration of future research directions unveils a trend from the past studies with a focus on single or few-fracture systems to complex fracture networks, with its “collective” behavior (Lei 2023). The collective behavior is manifested in fluid injection-induced seismicity, flow channeling, and changes in rock property anisotropy, all of which have major significance in many geo-energy applications. Three examples of research in the collective behavior of fracture networks undergoing coupled processes are presented. First is an effort to identify a few representative parameters characterizing the fracture network that play a controlling role in “collective” coupled THM behavior. Search and identification of such direct controlling parameters of the fracture network on major phenomena (such as induced seismicity and channelized flow) due to coupled THM processes may be a very fruitful direction of future research in this field. The second example of future research direction is to address the heterogeneity and hierarchy of the fractures in a fault or fracture zone which has been associated with major events observed in a number of important geo-energy projects. The effects of coupled processes in the complex structure of faults or fracture zones have not yet been adequately studied. The third example of

future research is at the opposite end of the first example; here it is shown that the behavior of fracture rocks under coupled processes may be controlled dominantly by a few key bridges. Identification, characterization, and evaluation of these key bridges should be one of the key research directions in the coming days.

Acknowledgements The author gratefully acknowledges the encouragement and interactions he had over the years with Paul Witherspoon, Neville Cook, Ove Stephansson, John Hudson, Lanru Jing, Johan Noorishad, Ivars Neretnieks, Ghislain de Marsily, Antonio Gens, Robert Zimmerman, Auli Niemi, Jonny Rutqvist, Jens Birkholzer, Ki-Bok Min, and others. More recently, he has benefited much through cooperation and discussions with Adriana Paluszny, Qinghua Lei, Bruno Figueiredo, Yunzhong Jia, Mrityunjai Sharma, and others. He specially thanks the DECOVALEX project and all its participants over the last 30 years during which the author had the privilege of participation and learning in all the detailed and in-depth discussions of the DECOVALEX workshops and meetings. Preparation of the present paper is partially supported by the U.S. Department of Energy under Contract Number DE-AC02-05CH11231 with Lawrence Berkeley National Laboratory and by the Swedish Radiation Safety Authority (SSM) through Uppsala University.

Funding Open access funding provided by Uppsala University.

Declarations

Conflict of Interest The author has no financial interest related to the work reported in this paper.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Bense VF, Gleeson T, Loveless SE, Bour O, Scibek J (2013) Fault zone hydrogeology. *Earth-Sci Rev* 127:171–192. <https://doi.org/10.1016/j.earscirev.2013.09.008>
- Birkholzer JT, Bond A (2022) DECOVALEX-2019 – an international collaboration for advancing the understanding and modeling of coupled Thermo-Hydro-Mechanical-Chemical (THMC) processes in geological systems. *Int J Rock Mech Min Sci* 154:105097. <https://doi.org/10.1016/j.ijrmms.2022.105097>
- Birkholzer JT, Tsang CF, Bond AE, Hudson JA, Jing L, Stephansson O (2019) Twenty-five years of DECOVALEX - scientific advances and lessons learned from an international research collaboration in coupled subsurface processes, *Invited Review Paper*. *Int Jour Rock Mech Mining Sci* 122:103995. <https://doi.org/10.1016/j.ijrmms.2019.03.015>
- Brixel B, Klepikova M, Jalali MR, Lei Q, Roques C, Krietsch H, Loew S (2020a) Tracking fluid flow in shallow crustal fault zones: 1. New in situ permeability measurements. *J Geophys Res Solid Earth* 125: e2019JB018200
- Brixel B, Klepikova M, Lei Q, Roques C, Jalali MR, Krietsch H, Loew S (2020b) Tracking fluid flow in shallow crustal fault zones: 2. Insights from cross-hole forced flow experiments in damage zones. *J Geophys Res Solid Earth* 125: e2019JB019108
- Davy P, Bour O, deDreuzy JR, Darcel C (2006) Flow in multiscale fractal fracture networks. *Geol Soc London Spec Public* 261:31–45. <https://doi.org/10.1144/GSL.SP.2006.261.01.03>
- deDreuzy JR, Davy P, Bour O (2000) Percolation parameter and percolation-threshold estimates for three-dimensional random ellipses with widely scattered distributions of eccentricity and size. *Phys Rev E* 62(5):5948–5952. <https://doi.org/10.1103/PhysRevE.62.5948>
- Faulkner DR, Jackson CAL, Lunn RJ, Schlische RW, Shipton ZK, Wibberley CAJ, Withjack MO (2010) A review of recent developments concerning the structure, mechanics and fluid flow properties of fault zones. *J Struct Geol* 32:1557–1575. <https://doi.org/10.1016/j.jsg.2010.06.009>
- Figueiredo B, Tsang CF, Rutqvist J, Niemi A (2015) A study of changes in deep fractured rock permeability due to coupled hydro-mechanical effects. *Int J Rock Mech Mining Sci* 79C:70–85. <https://doi.org/10.1016/j.ijrmms.2015.08.011>
- Figueiredo B, Tsang CF, Rutqvist J, Niemi A (2017) The effects of nearby fractures on hydraulically induced fracture propagation and permeability changes. *Eng Geol* 228:197–213. <https://doi.org/10.1016/j.enggeo.2017.08.011>
- Figueiredo B, Tsang CF, Niemi A (2020) The influence of coupled thermomechanical processes on the pressure and temperature due to cold water injection into multiple fracture zones in deep rock formation. *Geofluids*. <https://doi.org/10.1155/2020/8947258>
- Follin S (2008) Bedrock hydrogeology Forsmark. Site descriptive modelling, SDM-Site Forsmark. Swedish Nuclear Waste Management Company (SKB), report R-08-95
- Fox A, La Pointe P, Hermanson J, Öhman J (2007). Statistical geological discrete fracture network model. Forsmark modelling stage 2.2. Swedish Nuclear Waste Management Company (SKB), report R-07-46
- Gao K, Lei Q, Bozorgzadeh N, Chau V (2019) Can we estimate far-field stress using the mean of local stresses? An examination based on numerical simulations. *Comput Geotech* 116:103188
- Hudson JA, Tsang CF, Jing L (2017) Coupled THMC modeling for safety assessment of geological disposal of radioactive wastes: The DECOVALEX project (1992–2015). In: *Rock Mechanics and Engineering*, edited by Xia-Ting Feng, CRC Press, London. Volume 3, pp. 15–56
- Jia Y, Tsang CF, Hammar A, Niemi A (2022a) Hydraulic stimulation strategies in enhanced geothermal systems (EGS): a review. *Geomech Geophys Geo-energ Geo-resour* 8:211. <https://doi.org/10.1007/s40948-022-00516-w>
- Jia Y, Tsang CF, Lu Y, Niemi A (2022b) A study of fluid injection induced seismicity in crystalline rock as a function of a percolation parameter of pre-existing fracture network. *Proceedings of CouFrace 2022 Conference*, November 14–16, 2022, Lawrence Berkeley National Laboratory, Berkeley, California
- Jiang C, Wang X, Zhang F, Deng K, Lei Q (2022) Fracture activation and induced seismicity during long-term heat production in fractured geothermal reservoirs. *Rock Mech Rock Eng* 55:5235–5258
- Latham J-P, Xiang J, Belayneh M, Nick HM, Tsang C-F, Blunt MJ (2013) Modelling stress-dependent permeability in fractured rock including effects of propagating and bending fractures. *Int J Rock Mech Min Sci* 57:100–112

- Lei Q (2023) More is different: On the emergence of collective phenomena in fractured rocks. *Rock Mech Bull* 2:100080
- Lei Q, Gao K (2018) Correlation between fracture network properties and stress variability in geological media. *Geophys Res Lett* 46:3994–4006
- Lei Q, Gao K (2019) A numerical study of stress variability in heterogeneous fractured rocks. *Int J Rock Mech Min Sci* 113:121–133
- Lei Q, Tsang C-F (2022) Numerical study of fluid injection-induced deformation and seismicity in a mature fault zone with a low-permeability fault core bounded by a densely fractured damage zone. *Geomechan Energy Environ* 31:100277. <https://doi.org/10.1016/j.gete.2021.100277>
- Lei Q, Wang X (2016) Tectonic interpretation of the connectivity of a multiscale fracture system in limestone. *Geophys Res Lett* 43:1551–1558
- Lei Q, Latham J-P, Xiang J, Tsang C-F, Lang P, Guo L (2014) Effects of geomechanical changes on the validity of DFN representation of a realistic 2D fractured rock. *Int J Rock Mech Min Sci* 70:507–523
- Lei Q, Latham J-P, Tsang C-F, Xiang J, Lang P (2015) A new approach to upscaling fracture network models while preserving geostatistical and geomechanical characteristics. *J Geophys Res Solid Earth* 120:4784–4807
- Lei Q, Latham J-P, Xiang J (2016) Implementation of a joint constitutive model in finite-discrete element analysis of the geomechanical behaviour of fractured rocks. *Rock Mech Rock Eng* 49:4799–4816
- Lei Q, Latham J-P, Tsang C-F (2017a) The use of discrete fracture networks for modelling coupled geomechanical and hydrological behaviour of fractured rocks. *Comput Geotech* 85:151–176
- Lei Q, Latham J-P, Xiang J, Tsang C-F (2017b) Role of natural fractures in damage evolution around tunnel excavation in fractured rocks. *Eng Geol* 231:100–113
- Lei Q, Wang X, Xiang J, Latham J-P (2017c) Polyaxial stress-dependent permeability of a three-dimensional fractured rock layer. *Hydrogeol J* 25:2251–2262
- Lei Q, Wang X, Min K-B, Rutqvist J (2020) Interactive roles of geometrical distribution and geomechanical deformation of fracture networks in fluid flow through fractured geological media. *J Rock Mech Geotechn Eng* 12:780–792
- Lei Q, Gholizadeh Doonechaly N, Tsang C-F (2021) Modelling fluid injection-induced fracture activation, damage growth, seismicity occurrence and connectivity change in naturally fractured rocks. *Int J Rock Mech Min Sci* 138:104598
- Maillot J, Davy P, LeGoc R, Darcel C, deDreuzy JR (2016) Connectivity, permeability, and channeling in randomly distributed and kinematically defined discrete fracture network models. *Water Resour. Res* 52:8526–8545. <https://doi.org/10.1002/2016WR018973>
- Min KB, Rutqvist J, Tsang CF, Jing L (2004) Stress-dependent permeability of fracture rock masses: a numerical study. *Int J Rock Mech Min Sci* 41:1191–1210
- Munier R, Stanfors R, Milnes AG, Hermansson J, Triumf CA (2003) Geological site descriptive model—a strategy for the model development during site investigation. SKB R-03–07. Swedish Nuclear Waste Management Company (SKB), Stockholm
- Robinson PC (1983) Connectivity of fracture systems—a percolation theory approach. *J Phys A Math Gen* 16:605–614
- Sawada AM, Uchida M, Shimo M, Yamamoto H, Takahara H, Doe TW (2000) Non-sorbing tracer migration experiments in fractured rock at the Kamaishi Mine, Northeast Japan. *Eng Geol* 56(1–2):75–96. [https://doi.org/10.1016/S0013-7952\(99\)00135-0](https://doi.org/10.1016/S0013-7952(99)00135-0)
- Sawada AM, Saegusa H, Ijiri Y (2005) Uncertainty in groundwater flow simulations caused by multiple modeling approaches at Mizunami Underground Research Laboratory, Japan. *Am Geophys Union Geophys Monograph Series* 162:91–101. <https://doi.org/10.1029/162GM10>
- Sharma KM, Tsang CF, Geier J, Stothoff S, Pensado O, Niemi A (2023) Channel Network Model for Flow and Transport in Low-Permeability Fractured Rock and its Characteristics. Submitted to a *Scient J Under Rev*
- Stephansson O, Jing L, Tsang CF, editors (1996) Coupled thermo-hydrromechanical processes of fractured media—Mathematical and experimental studies, *Dev. Geotech Eng.*, volume 79. 575 pp. Amsterdam, New York: Elsevier
- Sun Z, Jiang C, Wang X, Zhou W, Lei Q (2021) Combined effects of thermal perturbation and in-situ stresses on heat transfer in fractured geothermal reservoirs. *Rock Mech Rock Eng* 54:2165–2181
- Tsang CF (1991) Coupled thermomechanical hydrochemical processes in rock fractures. *Rev Geophys* 29(4):537–551
- Tsang CF (2005) Is current hydrogeologic research addressing long-term predictions? *J Ground Water* 43(3):296–300
- Tsang CF, Doughty C (2003) A particle tracking approach to transport in a complex fracture. *Water Resour Res* 39(7):1174–1178. <https://doi.org/10.1029/2002WR001614>
- Tsang CF, Neretnieks I (1998) Flow channeling in heterogeneous fractured rocks. *Rev Geophys* 36(2):275–298
- Tsang CF, Niemi A (2013) Deep hydrogeology: a discussion of issues and research needs. *Issue Paper Hydrogeol J* 21–08:1687–1690. <https://doi.org/10.1007/s10040-013-0989-9>
- Tsang CF, Gelhar L, deMarsily G, Andersson J (1994) Solute transport in heterogeneous media: a discussion of technical issues coupling site characterization and predictive assessment. *Adv Water Resour* 17(4):259–264
- Tsang CF, Bernier F, Davies C (2005) Geohydrromechanical processes in the excavation damaged zone in crystalline rock, rock salt, and indurated and plastic clays—in the context of radioactive waste disposal. *Int J Rock Mech Min Sci* 42(1):109–125
- Tsang CF, Stephansson O, Jing L, Kautsky F (2009) DECOVALEX Project: from 1992 to 2007. *J Environ Geol* 57(6):1221–1238
- Tsang CF, Neretnieks I, Tsang Y (2015) Hydrologic issues associated with nuclear waste repositories, *Water Resour. Res.*, 51, [Special 50th Anniversary Issue of Water Resources Research]. 10.1002/2015WR017641
- Tsang CF (1987) Coupled Processes Associated with Nuclear Waste Repositories, C. F. Tsang, Editor, San Diego: Academic Press
- Wibberley CAJ, Kurz W, Imber J, Holdsworth RE, Collettini C (eds) (2008) The internal structure of fault zones: implications for mechanical and fluid-flow properties. Geological Society, London, Special Publications, 299
- Wilcock P (1996) Generic study of coupled T-H-M processes in the near field. *In* Coupled thermo-hydrromechanical processes of fractured media—Mathematical and experimental studies, Ove Stephansson, Lanru Jing and Chin-Fu Tsang, editors. *Dev. Geotech Eng.* Elsevier 79:311–340. [https://doi.org/10.1016/S0165-1250\(96\)80031-9](https://doi.org/10.1016/S0165-1250(96)80031-9)

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.